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Simultaneous Field Measurements of Turbulence and Water Quality in a Sub-Tropical Estuary in Australia

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Abstract

In natural systems, mixing is driven by turbulence, but current knowledge is very limited in estuarine zones. A series of detailed field studies was conducted in a small subtropical creek in eastern Australia. Hydrodynamic and physio-chemical parameters were measured simultaneously at high frequency to assess the complexity of the estuary and the interactions between turbulence and environment. The results provide an original data set to complement long-term monitoring. Unlike many such field observations, velocity and physio-chemistry (scalars) were measured herein with sufficient spatial and temporal resolutions to determine quantities of interest in the study of turbulence. In particular the results yielded contrasted outcomes, and the finding impacts on the selection of "key water quality indicators".

Introduction

Mixing and dispersion of matter in estuaries is of considerable importance. Applications include sediment transport, smothering of seagrass and coral, release of wastewater into ecosystems including from treated sewage effluent, and storm-water runoff during flood events. Current knowledge is limited : e.g., the vertical mixing coefficient is often approximated by the depth-averaged momentum exchange coefficient, while transverse mixing and dispersion coefficients are assumed constant over relatively long distances. Both sets of assumptions are untrue. Predictions of contaminant dispersion in estuaries must be therefore based upon empirical mixing coefficients that are highly sensitive upon the natural system and must be measured in-situ. Experimental findings are accurate only "within a factor of 10" at best and they can rarely be applied to another system [1,2,3]. Although mixing is driven by turbulence, the interactions between hydrodynamics, physio-chemistry and ecology are rarely considered together. There has been very little research done on turbulent mixing and dispersion in complete estuarine systems, in particular in subtropical zones. One reason is the complex behaviour of an estuary.

A series of field studies were conducted in the estuarine zone of Eprapah Creek (Australia) in 2003. The purpose of field works was to assess the complexity of a small estuarine system, and the interactions between hydrodynamics and water quality. The results provide a new understanding of basic mixing process in sub-tropical estuaries, while the experience highlights important issues and practical considerations.

Field site

Eprapah Creek (Long. 153.30º, Lat. -27.567º) is a sub-tropical stream located in the Redlands shire close to Brisbane city. Average hydrological conditions are listed in Table 1 for a 50-year period. Eprapah Creek flows directly to the Moreton Bay at Victoria Point (Fig. 1). It is basically 13.6 km long with about 3.8 km of estuarine zone. In the latter, the water depth is typically about 1 to 2 m mid-stream, the width is about 20-30 m and the tides are semi-diurnal with a range of about 1.5 m. The catchment (~ 39 km^2 area) is mostly urban in the lower reaches and semi rural/rural residential in the upper reaches. The estuary includes two conservation areas hosting endangered species (e.g. koalas, swamp wallabies, sea eagles), some marinas and boat yards, and a sewage plant impacting heavily on the natural system. .

Although water quality and ecology have been closely monitored at Eprapah Creek (Victoria Point QLD) for more than 30 years, the creek was heavily polluted in 1998 by illegal discharges of TBT and chemical residues. The catchment has been adversely affected by industrial poultry farms, land clearance and semi-urban development. Recent works included the constructions of new shopping centres and residential lots.

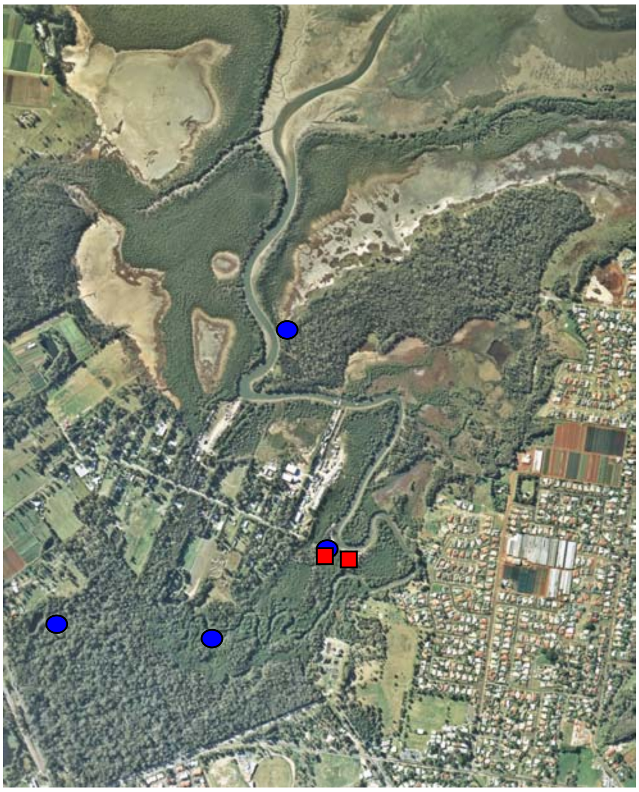


Fig. 1 - Aerial photograph of Eprapah Creek estuary (Courtesy of Queensland Department of Natural Resources and Mines, 2001)
Blue circle: water quality sampling station - Red square: instantaneous velocity and physio-chemical measurement sites.

Experimental Methods

Field works took place on three different days (Table 2). They involved more than 80 people, including researchers, students, professionals and local community groups for a single-day each time. Tidal and weather conditions are summarised in Table 2. Several sites were simultaneously monitored at locations AMTD 0.6, 2, 2.1, 3.1, 3.4 and 3.8 km for Sites 1, 2, 2B, 3, 3B and 4 respectively, where AMTD is the upstream distance from river mouth. (Sites 1, 2, 3 and 4 are marked with a blue circle on Figure 1.) At each site, a series of hydraulic and water quality data were recorded from the bank: e.g., water elevations, surface velocity, air and water temperatures, conductivity, pH, dissolved oxygen, turbidity. Most readings were taken every 15 to 30 minutes. Vertical profiles of physio-chemical parameters were conducted in the middle of the creek at several sites. They were performed at high tide and during ebb flow using a water quality probe YSI™6920 lowered from a boat drifting with the flow. Measurements included water temperature, conductivity pH, conductivity, dissolved oxygen content and turbidity taken every 20 to 50 cm.

Parameters	Value	Units
Air temperature at 09:00 :	20.5	ºC
Average humidity at 09:00 :	67	%
Average wind speed at 09:00:	8.6	km/h
Average yearly rainfall :	1284.3	mm
Maximum monthly rainfall :	909.7	mm
Maximum daily rainfall :	241.0	mm
Average number of rainy days :	116	days/year
Average sunny days :	81	days/year
Average number of overcast days :	60	days/year

Table 1 - Average hydrological conditions in Eprapah Creek catchment for the period 1953-2003 (Ref.: Bureau of Met.)

	4 Apr. 2003	17 July 2003	24 Nov. 2003
Tides (Brisbane bar):	04:58 (0.53 m) 10:49 (2.02 m) 17:06 (0.43 m) 23:17 (2.20 m)	23:42 (2.41 m) 06:30 (0.46 m) 12:01 (1.73 m) 17:47 (0.45 m)	03:09 (0.09 m) 09:36 (2.52 m) 16:11 (0.34 m) 21:39 (1.91 m)
Study period:	06:00-18:00	06:00-14:05	07:00-16:00
ADV/YSI6600 record period:	10:10-14:05	06:10-14:05	09:18-15:55
Weather :	Sunny	Overcast	Overcast with few showers
Water temp. (ºC) :	23.7 [20.4-28.4]	16.7 [15.5-18.5]	25.5 [22.7-28.0]
Air temp. (ºC):	22.2 [15.5-29]	17.2 [10.5-21.5]	-- [19-29]
Conductivity (mS/cm):	34.5 [23.9-48.3]	37.2 [29.8-48.4]	50.0 [42.7-55.1]
D.O. (% sat):	0.85 [0.62-1.0]	0.82 (*) [0.66-1.06]	0.81 [0.76-0.85]
pH	6.8 [6.4-7]	7.4 [6.6-7.8]	7.8 (*) [7.4-8.0]
Turbidity (m Secchi)	0.68 [0.53-1.0]	0.84 [0.5-1.2]	--
Turbidity (NTU)	9.4 [5.8-13.9]	11.0 [7.2-*24.6*]	19.9 [7.1-43]

Table 2 - Summary of experimental flow conditions and measurements at Site 2 (AMTD 2 km) - Averages and extremes in brackets

At one site, a Sontek™ ADV velocitymeter and a physio-chemical probe YSI™6600 were deployed and data-logged continuously at respectively 25 Hz and 0.2 Hz (or 0.5 Hz). The probes were located at Site 2B on 4 April and 24 Nov. 2003, and at Site 2 on 17 July 2003. They were installed about the middle of the channel in a moderate bend to the right when looking downstream (Fig. 2). The probes were located 14.2 m, 8.0 m and 10.8 m from the left bank on 4 April, 17 July and 24 Nov. 2003 respectively. The sensors were positioned 300 mm apart horizontally and held by a metallic frame sliding on two poles (Fig. 2A). All sensors were located 0.50 m beneath the free-surface and maintained at a constant depth below the free-surface for all studies. The probes were installed outside of the support system to limit the support wake effects. Further details on the experimental procedures are available in Chanson et al. [4].

Data accuracy

For measurements from the bank, the data accuracy was about 1 cm for water level elevation, 0.2 to 0.5 ºC for water temperature, 1 to 2% for conductivity, 0.2 to 0.5 for pH measurement with pH paper, 5 cm on turbidity Secchi disk length, 10% on the surface velocity and 5 to 10% on the dissolved oxygen concentration. With the water quality probes YSI6920 and YSI6600, the data accuracy was : ±2% of saturation concentration for D.O., ±0.5% for conductivity, ±0.15ºC for temperature, ±0.2 unit for pH, ±0.02 m for depth, ±1% of reading for salinity, and ±5% for turbidity. No information was available on the data accuracy on chlorophyll levels.

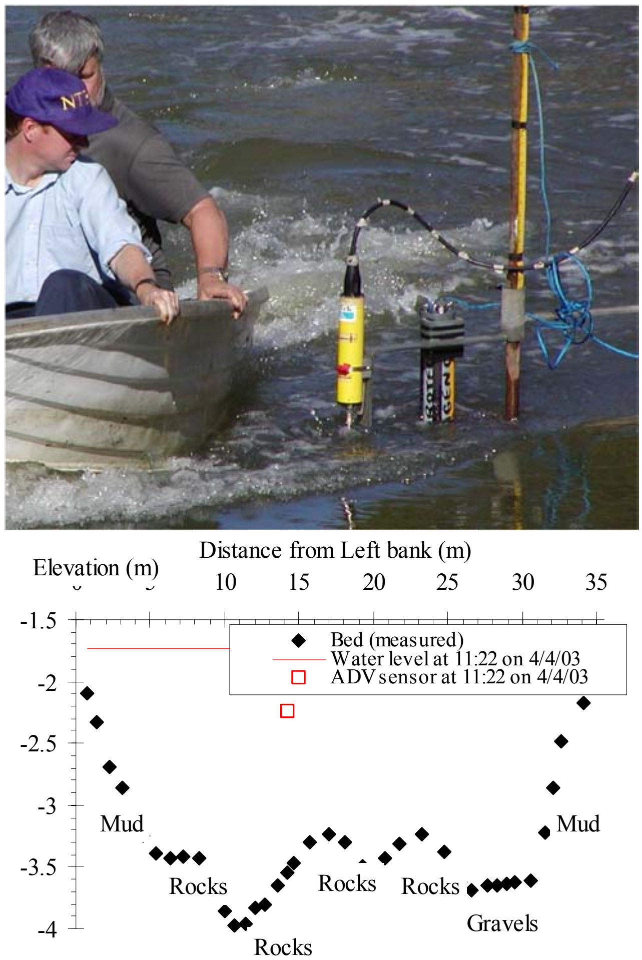


Fig. 2 - Simultaneous measurements of physio-chemistry and turbulence. (A) Probes in position, looking upstream. (B) River cross-section at Site 2B looking downstream.

General Observations

For all studies, the tidal influence was felt up to Site 3B (AMTD 3.5 km) but not at Site 4. The latter site was basically a freshwater system each time. For the greatest tidal range (24 Nov. 2003), a very-shallow water zone was seen at low tide between Site 2B (AMTD 2.1 km) and the sewage plant (AMTD ~ 2.6 km) : i.e., depths less than 0.3 to 0.5 m. For such very low tides, the "bar" acted as a weir. It reduced drastically mass exchanges between upper and lower estuarine zones at low tides.

Physio-chemical observations were conducted systematically from the bank and from a boat mid-stream at several longitudinal locations. Water temperature data were affected predominantly by the natural heating of the Sun, and by the flood tide bringing temperate waters from the Moreton Bay. Dissolved oxygen (DO) measurements showed more oxygenated downstream waters and maxima around high tide. Basically dissolved-oxygen saturated waters were brought in by the flood tide. Turbidity data indicated consistently a greater water clarity at high tide and at beginning of ebb flow, while the observations were about constant along the creek. Water conductivity data followed the tidal cycle with an influx of saltwater during the flood flow and a reflux during the ebb in the intertidal zone, with an overall decrease in time-average conductivity with increasing distance from the mouth. A decrease in pH with increasing distance from the river mouth was consistently observed, suggesting slightly acidic waters in the upstream reach. Vertical profiles of water quality parameters showed that the distributions of water temperature, dissolved oxygen content, turbidity and pH were reasonably uniform for all studies. Conductivity data showed however some stratification with a fresh water lens above a saltwater wedge. The stratification was possibly the strongest on 4 April 2003 because of freshwater runoff.

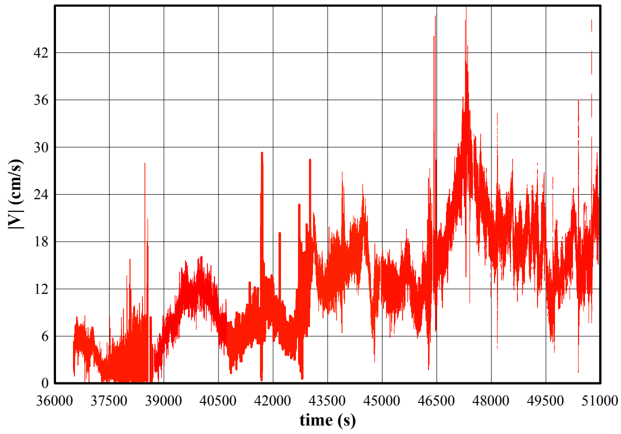
Short-Term Fluctuations

Short-term fluctuations in velocity and physio-chemical parameters were systematically investigated mid-estuary (AMTD 2 km). Turbulent velocity records, measured with the ADV, suggested distinct periods : i.e., a slack time around high and low tides, and some strong flushing during the flood tide (17/07/03) and ebb tides (4/04/03 & 24/11/03). Around high and low tides, the velocity magnitudes were small (i.e. less than 10 cm/s), and the velocity direction was highly fluctuating. The velocity magnitude increased with time after slack, and the strongest currents were observed during mid-ebb tides (4/04/03 & 24/11/03) with instantaneous velocities of about 0.2 to 0.35 m/s. Detailed records showed consistently significant time fluctuations of both velocity magnitude and direction, with fluctuations in instantaneous velocity directions of typically 20 to 30º. Instantaneous water quality results showed relatively small fluctuations of water quality parameters with time. These fluctuations were at least one order of magnitude smaller than observed turbulent velocity fluctuations. The findings might suggest that the estuary was reasonably well-mixed in terms of temperature, pH, DO and turbidity, although the turbulence was not homogeneous in the waterway.

Figures 3 and 4 present instantaneous velocity and physio-chemical data recorded on 4 April 2003. (For these data, the surveyed cross-section of the estuary is shown in Figure 2B.) Figure 3 presents instantaneous velocity magnitude |V| and direction θ, with θ = 0 in the downstream direction and θ > 0 towards the left bank. In Figure 4, the right vertical axis corresponds to temperature and pH data, while the left vertical axis scales the dissolved oxygen content (DO) and salinity (ppt).

In natural systems, the flow motion is characterised by unpredictable behaviour, strong mixing properties and broad spectrum of length scales [5]. There is however some coherence caused by bursting phenomena and large-scale vortical motion. The present data set highlighted large fluctuations of instantaneous velocity direction which is characteristic of the passage of coherent vortical structures (Fig. 3). The probability distribution functions of θ were approximately Gaussian that is consistent with random turbulent processes.

In meandering channels, Blanckaert and Graf [6] highlighted the existence of a small outer bank recirculation cell. Such recirculation zones were systematically observed at Site 2 (AMTD 2 km). Toad fish, a relatively slow fish specie, were seen utilising these outer bend zones for feeding. Visual observations and toad fish behaviour indicated spatial and temporal variations of these recirculation regions. Their occurrence is important since outer bend cells contribute to a reduction in bend scouring. Their existence confirms that the turbulence was not homogeneous across the river.



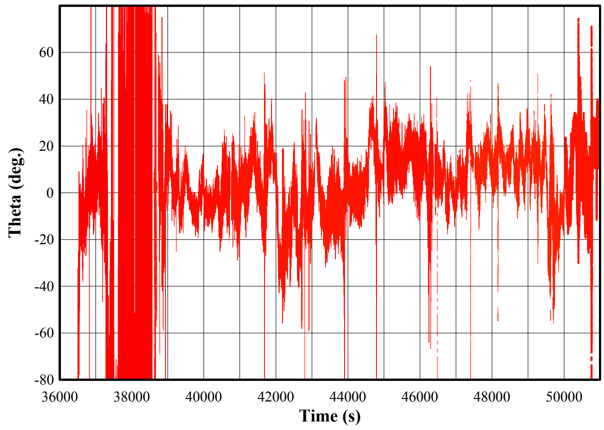


Fig. 3 - Instantaneous velocity measurements on 4 April 2003 during high tide slack and early ebb tide. The horizontal axis is the clock time in seconds with t = 0 at 0:00. (A) Velocity amplitude |V|. (B) Velocity direction θ.

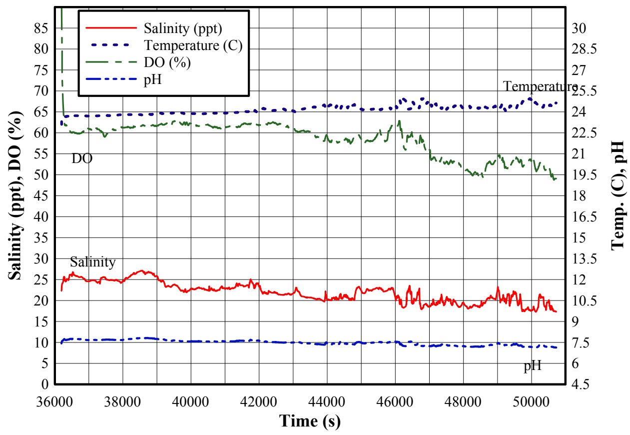


Fig. 4 - Instantaneous physio-chemical parameters on 4 April 2003 during high tide slack and early ebb tide.

Discussion

Continuous measurements showed important fluctuations in instantaneous velocity and physio-chemical parameters caused by navigation (e.g. Fig. 2A). Boat passages were typically associated with large fluctuations in velocity for a few seconds, followed by a longer period, lasting for several minutes, of fluctuations in both velocity and physio-chemical parameters. While the data implied some mixing induced by wake waves and propeller motion, there were longer-lasting interactions between boat-induced turbulence and secondary circulation in the river. These might explain observations of significant fluctuations in turbidity, conductivity and temperature following boat passage.

A statistical analysis of instantaneous physio-chemical records was performed. The relevant time scales $T_{0.5}$ were typically about 1 to 4 minutes for all parameters and flow periods, where $T_{0.5}$ is the time delay for which the auto-correlation coefficient was 0.5. $T_{0.5}$ must be a significant time scale for river mixing processes. The results showed further strong correlations between pH and conductivity that is consistent with both variables being related to ion concentration in water. pH data lagged typically by about 5-10 sec. behind conductivity data. Possible explanations might include mixing processes or difference in sensor response time.

Experiences and Outcomes

Practical Considerations

Careful preparation of field works is crucial. In particular, all the instrumentation must be thoroughly calibrated and tested beforehand. Present experience demonstrated recurrent problems with the ADV velocitymeter evidenced by high levels of noise and spikes in the 3 velocity components. In the stream, the velocity fluctuations characterise the combined effects of the Doppler noise, velocity fluctuations and installation vibrations. Lemmin and Lhermitte [7] and Chanson et al. [8] discussed the inherent noise of an ADV system. Further spikes may be caused by aliasing of the Doppler signal. Goring and Nikora [9] discussed techniques to eliminate these. Some problem was also experienced with the vertical velocity component. Calibration tests in laboratory failed, possibly because of the effects of the wake of the stem. Since the probe was mounted vertically downlooking, vertical velocity data were discarded. Herein the ADV velocity data were cleaned by removing communication errors, low signal-to-noise ratio data (< 5dB) and low correlation samples (< 70%), and they were "despiked" using a acceleration thresholding method. Yet, during periods of low velocity, the ADV Doppler noise and spikes predominated causing large fluctuations in velocity around zero. This can be observed in Fig 3B in the range 37,500-38,500 s. When the direction (θ) is calculated, this fluctuation is greatly increased because there is no predominant flow direction as shown during the corresponding time in Fig 3B. The writers' experience at Eprapah Creek suggests that most classical "despiking" techniques are unsuitable to estuarine data, and data errors may still exist in the present data sets.

Personal experiences

Field works provided unique personal experiences to all people involved, and facilitated interactions between groups with different background and interests. Key interactions involved university researchers and students, local community, and government institutions. Field works contributed to the students' personal development and complemented traditional lectures, as strongly supported by anonymous student feedback [10]. Student comments emphasised their enhanced motivation. Group work contributed to new friendships and openings: e.g., between civil and environmental students, between students, academics and professionals involved in the studies. These personal experiences are at least as important as the academic and scientific experience, although this aspect is poorly understood from university hierarchy, administration clerks, managers and politicians.

Definition of key water quality indicators

Overall this series of field measurements provided consistently contrasted outcomes in terms of natural system health. Fish sampling and bird observations suggested a dynamic eco-system [4]. Velocity measurements indicated high turbulence levels and a strong flushing process in the estuary. But other results highlighted poor physio-chemical parameters in the upstream sections of the estuary. Serious concerns included low dissolved oxygen and pH levels (Sites 3 and 4), surface slicks (Sites 2 and 3), large numbers of exotic fish (e.g. Sites 3 and 4) competing with native fish species, and surface runoff (e.g. construction sites, shopping centres). All these results demonstrated on-going pollution in the estuary. Clearly a major issue is the definition of a limited number of "key indicators", which could describe the complexity of sub-tropical estuaries.

Summary and Conclusion

Detailed investigations in a small subtropical estuary provided a broad range of simultaneous data encompassing hydrodynamics and physio-chemistry. The measurements yielded contrasted outcomes. While some results were positive, others demonstrated on-going pollution. Field works provided further unique personal experiences to all individuals involved.

The field results obtained at Eprapah Creek bring new lights into the complexity of the estuarine system, but also thought-provoking outcomes. It is clear that basic mixing processes are driven by turbulence. However its impact on a natural system cannot be comprehended without simultaneous measurements of hydrodynamic, physio-chemical and ecological parameters, implying substantial instrumentation, human resources and broad-based expertise. Genuine inter-disciplinary research is essential and it can offer new approaches: e.g., using fish activities to characterise recirculation zones in shallow waters.

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